

> Cyber-Physical Systems

Driving force for innovation in
mobility, health, energy and production

acatech (Ed.)

acatech POSITION PAPER



Springer Vieweg



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NATIONAL ACADEMY OF
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SUMMARY

Embedded hardware and software systems are decisive driving forces for innovation in the export and growth markets of German industry. They crucially expand the functionality and, as a result, the practical value and competitiveness of vehicles, aircraft, medical equipment, production plants and household appliances. Today, about 98 percent of microprocessors are embedded, connected with the outside world through sensors and actuators. They are increasingly connected with one another and the internet. The physical world and the virtual world – or cyberspace – are merging. Cyber-physical systems (CPS) are being developed that are part of a globally networked future world, in which products, equipment and objects interact with embedded hardware and software beyond the limits of single applications. With the help of sensors, these systems process data from the physical world and make it available for network-based services, which in turn can have a direct effect on processes in the physical world using actuators. Through cyber-physical systems, the physical world is linked with the virtual world to form an *Internet of Things, Data and Services*.

Some examples of early cyber-physical systems – such as networked navigation software – already exist today. With the help of mobile communication data, the software deduces information on traffic jams from current movement profiles for improved route guidance. Further examples include assistance and traffic control systems from the fields of avionics and railway transportation. In these cases, the systems actively exercise control.

Future cyber-physical systems will contribute to safety, efficiency, comfort and human health like never before. They will therefore contribute to solving key challenges of our society, such as the aging population, limited resources, mobility, or the shift towards renewable energies, to name but a few fundamental fields of application. As part of a smart grid, cyber-physical systems will control the future energy network consisting of a multitude of renewable energy producers. In the future, they will make transport safer

through coordination, and they will reduce CO₂ emissions. Modern smart-health systems will network patients and doctors, facilitate remote diagnoses, and provide medical care at home. Internet-based systems for remote monitoring of autonomous production systems are being developed for manufacturing, logistics and transportation. One of the next steps is self-organization. Machines will autonomously control their maintenance and repair strategy depending on the degree of workload, and ensure backup capacities to maintain production in the case of maintenance-related interruptions.

Cyber-physical systems have a highly disruptive effect on market structures. They will fundamentally change business models and the competitive field of play. New suppliers of services based on cyber-physical systems are penetrating the markets. Revolutionary applications will facilitate new value chains, transforming the classic industries such as the automobile industry, the energy sector and production engineering.

Cyber-physical systems will pose new challenges to science and research. How should heterogeneously networked structures be handled that require an integral systemic view and interdisciplinary cooperation between mechanical engineering, electrical engineering and computer science? How can cyber-physical systems be mastered technically? And how should they be built, operated, monitored and maintained?

In terms of embedded systems, Germany is a world leader and also occupies a leading position in the market for security solutions and corporate software. In addition, Germany traditionally has a high level of engineering competence in the development of complex system solutions and has extensive research knowledge in semantic technologies and embedded systems. Despite this favourable starting position, Germany must also consider its weaknesses with regard to the development of cyber-physical systems. Germany has to do some catching up in internet competence –

in research and applications, development platforms and operator models as well as with innovative solutions for user-centred human-machine interfaces. On the other hand, the US National Science Foundation has been promoting the subject of cyber-physical systems since 2006 with numerous projects and programmes.¹

If Germany wants to secure a position as world leader in the use of innovative cyber-physical systems, rapid action by politicians together with stakeholders from science, the economy and society is required due to the tight time frame. The objective should be to master technology and its economic use and to focus on the social acceptance of cyber-physical systems. Taking into account the National Roadmap Embedded Systems (NRMES) 2009² for the further development of embedded systems, in order to overcome the technical, economic, social and political challenges connected with cyber-physical systems, acatech recommends:

1. As **technical prerequisites** for cyber-physical systems, mobile internet access and access to the physical infrastructure need to be promoted. This includes engineering of sensors and actuators, algorithms for the adaptive behaviour of networked systems and ontologies to interlink such autonomous systems. Development and operator platforms should be set up and expanded.
2. **Interoperability standards** need to be developed, and standardization activities need to be supported on international committees.
3. **Human-machine interaction** needs to be further developed in the fields of research, training and practical implementation. Human factors, such as the tailored logic of workflow, situational adequacy, usability of equipment and ergonomics issues, need to be explored integrally.
4. The existing legal situation with regard to the security and safety of cyber-physical systems needs to be adapted, especially in terms of **privacy protection**. A working group consisting of academics, lawyers and politicians is to be created to develop a concept for handling personal data in cyber-physical systems.
5. A **dialogue** about the benefits of social innovations created by cyber-physical systems needs to be initiated. It is necessary to involve the general public in the development of cyber-physical systems and to inform them on security and safety issues.
6. Specific platforms need to be established to explore **new business models for cyber-physical systems**. These business models need to be analyzed as part of a secondary research project.
7. Platforms and joint research projects specifically involving **SMEs** have to be created for the promotion of cyber-physical systems. SMEs should get simplified access to research projects. Spin-offs, particularly from universities, should be promoted.
8. A central national **research and competence centre** for the Internet of Things, Data and Services and the World Wide Web, which deals with all the issues in the field of global networks, has to be set up.
9. Existing **studies and training courses** (computer science, engineering, business management) need to be adapted to the requirements of cyber-physical systems. New interdisciplinary courses about cyber-physical systems need to be created.
10. German science should dedicate itself particularly to interdisciplinary projects on cyber-physical systems.

¹ See National Science Foundation 2011.

² See ZVEI 2009.

Integrated and **interdisciplinary fields of research** on cyber-physical systems should be promoted specifically in innovation alliances made up of industry and research participants.

11. The establishment of relevant CPS **showcases** for pilot applications and other efficient forms of mediation (such as Living Labs) can contribute to raising awareness of the subject early on, within the relevant export groups (particularly in SMEs) as well as the general public.

The acceptance of these new technologies by society is decisive for the success of cyber-physical systems. Cyber-

physical systems elevate the requirements of privacy and information security to a new level. In the future, immense volumes of highly important data will flow through the networks. The confidence of the general public in this new technology also depends on the security and the transparency of such flows of data.

Cyber-physical systems have major significance for a multitude of key issues in the future. For this reason, it is essential that the German government takes cyber-physical systems into account in its strategies for energy and resources, as well as in its high-tech and ICT strategy. And ultimately, the subject of transition to renewable energies also has to become part of an overall cyber-physical systems strategy.

PROJECT

This position was developed on the basis of the acatech STUDY *agendaCPS – Integrated Research Agenda for Cyber-Physical Systems* (Geisberger/Broy 2012).

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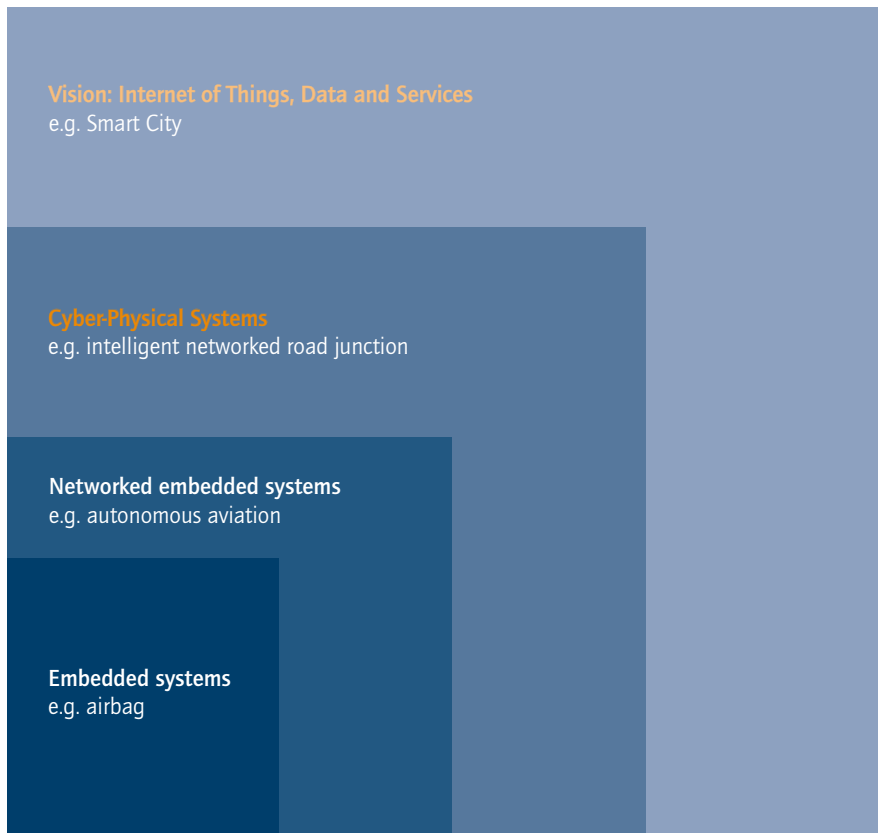
1 CYBER-PHYSICAL SYSTEMS – CHANGING ECONOMY AND SOCIETY

Information and communication technologies are strong driving forces of innovation. Two of them act as crucial driving forces in this matter:

- embedded software-intensive systems, as found in virtually all high-tech products and systems today, for example in devices, vehicles, aircraft, buildings and production systems, whose functionality is characterized decisively by such systems;
- global networks like the internet and the data and services available on the World Wide Web.

These two strong fields of innovation merge together into cyber-physical systems. An increasing number of devices and objects now have computers embedded in them, which interact with the physical world using sensors and actuators and exchange information with one another. Mobile devices, such as smartphones, are now being used by millions of people. RFID (Radio Frequency Identification) technology is used, for example, to automatically monitor billions of transportation processes. Previously closed systems are increasingly opening up and are being connected to other systems to make networked

Figure 1: The evolution of embedded systems into the Internet of Things, Data and Services



applications. Using cyber-physical systems, the physical world is being linked seamlessly with the virtual world of information technology into an Internet of Things, Data and Services.

Fig. 1 illustrates the vision of the global "Internet of Things, Data and Services" as an evolutionary development of embedded systems by networking them via the internet. Closed embedded systems, such as airbags, are the starting point. Recommendations for the move towards local networked embedded systems were developed back in 2009 in the National Roadmap Embedded Systems. The acatech STUDY agendaCPS is expanding the range to include global networking. One example is an intelligent road junction, which uses data from traffic jam alerts.

Cyber-physical systems are an "enabling technology", i.e. they enable numerous innovative applications. The profound changes and challenges in the context of cyber-physical systems should be seen in relation to and in interaction with other fields of innovation in modern technology. They will be described in detail below.

Corresponding to "Moore's Law", the speed of development of information and communication technology is rapid. In 1965, Gordon Moore, co-founder of the processor manufacturer Intel, postulated that the number of switching networks on one chip and, thus, the processing power of digital systems would double every one and a half years and remain at the same price. This exponential growth in the performance of digital information processing systems stimulates a close interplay of technological innovation, economic dynamics and social change.

Cyber-physical systems promote this dynamic by linking physical processes with the virtual world. Used cor-

rectly, cyber-physical systems make a decisive contribution to overcoming key social challenges, such as the aging population, climate change, health, safety, the switch to renewable energy, megacities, limited resources, sustainability, globalization and mobility. This is illustrated in the scenarios of the acatech STUDY agendaCPS.³ This development is reinforced by the rapid spread of global digital networks, such as the internet, and global access to data and services via "cloud computing". Cloud computing describes a new information technology paradigm, according to which resources of information technology (IT) – i.e. processing power, memory, applications and data – are dynamically supplied, managed and accounted for using networks. Consequently, IT resources can be procured and used "out of the cloud".⁴

The German government has been promoting research into fundamental aspects of cyber-physical systems since 2005 as part of the high-tech strategy 2020 and the ICT strategy 2015. In addition, comprehensive recommendations for action for the targeted promotion of embedded systems were developed in the National Roadmap Embedded Systems (NRMES) in 2009. The deficits and challenges listed in the NRMES still represent current issues – even for cyber-physical systems:

- The role of cyber-physical systems as a cross-sectional technology and driving force of innovation is still not sufficiently perceived by industry.
- Cross-industry standardization is lacking.
- The manufacturers of individual components are inadequately networked.
- Heterogeneity and isolated solutions prevail.
- Often, there is a dependence on individual suppliers with resulting economic problems.
- There is a shortage of qualified engineers.

³ The comprehensive acatech STUDY agendaCPS will be published in March 2012 (Geisberger/Broy 2012).

⁴ See Cloud Computing Action Program of the Federal Ministry of Economics and Technology (October 2010), BMWi 2010a, p. 10.

acatech recommends:

a further consistent implementation of the recommendations for action from the National Roadmap Embedded Systems 2009 and the continuation of the "Intelligent Objects" line of action stated in the high-tech strategy 2020.

This position and the underlying agendaCPS study are meant to contribute to an Internet of Things, Data and Services in order to preserve and expand Germany's competitiveness with regard to the rapid transition in the ICT sector. The objective is to establish Germany as both a leader in single components or technologies for cyber-physical systems and as a global innovation leader for solutions using cyber-physical systems.

2 CYBER-PHYSICAL SYSTEMS – MERGING THE PHYSICAL AND VIRTUAL WORLDS

Cyber-physical systems are systems with embedded software (as part of devices, buildings, means of transport, transport routes, production systems, medical processes, logistic processes, coordination processes and management processes), which:

- directly record physical data using sensors and affect physical processes using actuators;
- evaluate and save recorded data, and actively or reactively interact both with the physical and digital world;
- are connected with one another and in global networks via digital communication facilities (wireless and/or wired, local and/or global);
- use globally available data and services;
- have a series of dedicated, multimodal human-machine interfaces.

The result of the connection of embedded systems with global networks is a wealth of far-reaching solutions and applications for all areas of our everyday life. Subsequently, innovative business options and models are developed on the basis of platforms and company networks. Here, the integration of the special features of embedded systems – for example, real-time requirements – with the characteristics of the internet, such as the openness of the systems, represents a particular technical challenge.

2.1 DRIVER OF INNOVATION AND PROCESS OPTIMIZATION

Information and communication technology (ICT) has exhibited a series of rapid technological advancements since it came into existence. Evermore miniaturised integrated circuits, the exponential growth of processing power and bandwidth in networks, as well as increasingly efficient search engines on the internet are just a few examples.

Information technology (IT) is omnipresent; as a result, *ubiquitous computing* is a reality. Consequently, the advancement in information and communication technology is not only leading to the horizontal connection of previously separated industries, but also increasingly to the vertical integration of ICT as a part of products. Virtually every industry today uses ICT to improve both its internal processes and its products. In the automobile industry, for example, the race to network vehicles has begun.⁵

The dynamics described will have a major effect on the business models and prospects of a multitude of industries in which Germany has a leading role. Cyber-physical systems have an enormous innovation potential, which will lead to a fundamental transition in the economy and in private and professional everyday life.

Virtually no other industry shows the potential and significance of cyber-physical systems more boldly than the **automobile industry**. The majority of innovations to increase safety, comfort or efficiency are already based on embedded systems. In the future, cyber-physical systems will be increasingly used to network vehicles extensively, both with one another and also with devices, data and services outside of the vehicle. As the automobile industry accounts for more than a third of the total industrial research and development investments in Germany (approx. 20 billion euros) and provides approx. 715,000 jobs,⁶ it is essential for Germany, as a business location, to aspire to achieve a leading role in the research, development and use of cyber-physical systems. A major opportunity here is the connection with **electromobility**. For example, route management for battery-operated cars is virtually inconceivable without cyber-physical systems.

Medical engineering is one of the greatest fields of growth in the world. Investment in research and development in the industry makes up about eight percent of the

⁵ See CARIT 2011.

⁶ Bretthauer 2009.

turnover – about twice the industrial average.⁷ It is estimated that the turnover in medical engineering in Germany will increase by about eight percent per year up to 2020. Besides telemedical patient monitoring, equipment networking and the expansion of the functionality of existing devices, cyber-physical systems offer a multitude of opportunities, for example to optimize emergency deployments and increase efficiency in hospitals. Many of these innovations can only arise through communication between previously isolated devices and the linking of data which was previously collected and held separately. Demographic change will lead to an increased demand for AAL solutions (*Ambient Assisted Living*), which can only be realized with cyber-physical systems.

The increasing demand for energy, the simultaneous shortage of fossil resources and the increased significance of climate protection are presenting numerous challenges for the **energy industry**, **energy consumers** (companies and private households) and politicians. The energy system needs to adapt to the volatile availability of electricity from renewable sources and the decentralization of energy production. Cyber-physical systems here play a decisive role as a fundamental component of intelligent power networks, or so-called smart grids: network management, consumption optimization and production planning can only be implemented through networked systems.

In **mechanical and plant engineering and in automation technology**⁸ as well, both the potential and the challenges of cyber-physical systems are becoming clear. The global networking of systems and factories of different operators – with one another and with comprehensive production planning, energy management and warehouse systems – allows

for energy savings, higher efficiency and, last but not least, a higher degree of flexibility.

Cyber-physical systems will lead to major changes, especially in the field of **mobile communication**. The networking and integration of mobile devices with comprehensive sensor systems using a reliable and efficient mobile communication infrastructure form the basis for many applications of cyber-physical systems. By 2014, the proportion of the German population using the mobile internet will have grown from 21 to more than 40 percent.⁹ **Localization and navigation** also have major growth potential. By 2014, the global market for devices with integrated satellite navigation receivers is expected to have doubled in comparison with the level of 2009.¹⁰

Agriculture, which is already optimizing processes with the help of information technology, is another field for the use of cyber-physical systems. Comprehensive intelligent systems link GPS position location, monitoring technology and sensor networks to determine the current state of agricultural land and support agricultural providers in the optimized fertilization of fields. As a result, the efficiency of agricultural processes is increased and soil can be used with an increased focus on ecological responsibility.

In the field of **goods transport logistics**, RFID has become prevalent as a passive technology for identification, localization and status detection. Up to now, these systems only permitted relatively imprecise determination of the location of goods and only a rare updating of the status of goods. The use of cyber-physical systems in logistics offers opportunities for new applications with intelligent active objects, for example integrated position tracking and status enquiries

⁷ Study on behalf of HSH Nordbank into the future industry of medical engineering: Bräuninger/Wohlers 2008.

⁸ About 913,000 people were employed in German mechanical and systems engineering at the end of 2010; German companies are market leaders in numerous sub-industries. See VDMA 2011.

⁹ BMWi 2010c. The introduction and implementation of "long term evolution" (LTE) mobile radio standards and networks is essential for the continuous networking of devices.

¹⁰ ABI Research 2009.

in real time. Its use also opens up new options for the planning and monitoring of deliveries. Global tracking and tracing of original products using cyber-physical systems can also effectively prevent the introduction of counterfeit goods into the logistics process.

Cyber-physical systems facilitate greater comfort, safety and energy efficiency (for example through intelligent systems for the management of decentralised energy production such as photovoltaics), in **home and building automation**,¹¹ for example in residential buildings. In commercial and manufacturing buildings, there is additional potential, for example if building and machine control systems interact with one another. Due to such innovations, the building automation industry anticipated a growth in turnover of five percent in 2011.¹² Future growth will be decisively driven by the fact that investments in measuring, control and regulating technology as well as in the related building services management systems pay for themselves considerably more quickly than investments in other energy-related schemes.

Based on platforms consisting of cyber-physical systems, clusters of companies from various industries and segments of industry are developing to create a comprehensive range of services. Hardware and software manufacturers, application companies and telecommunication suppliers are merging their competences that are needed to construct and operate cyber-physical systems. This facilitates cross-industry product innovation, which ignores existing market boundaries and accelerates the merger of previously separate markets.

2.2 DRIVING FORCE OF THE DEVELOPMENT OF CYBER-PHYSICAL SYSTEMS

The development and distribution of cyber-physical systems is promoted by three converging trends:

(1) *Smart embedded systems, mobile services, and "ubiquitous" computing.*

Intelligent embedded systems form one part of cyber-physical systems and are already functioning cooperatively and as networks today, although still mostly as closed systems. Localized services and assistance functions already exist, predominantly in the automobile industry and aeronautics industry, as well as in telecommunications, automation technology and production. An increase in networking, interaction, cooperation and use of mobility services and other network services makes such services more versatile and sophisticated.

(2) *Internet-based business processes in two supplementary forms:*

- a) "Intelligent" and networked objects (for example, using RFID technology) are mainly used in trade and logistics. Increasingly, the digital product memory of objects is also used for process optimization, for example in the flow of goods. The objects adapt flexibly to software-controlled business processes and interact with customers via the web. For example, the internet can be used to track where a product currently is within a logistics chain.
- b) IT services of this kind are increasingly outsourced into the "cloud", i.e. to external service providers; this makes their operation independent from a data centre at a certain location. IT systems also need to be set up for outsourcing classic IT and administrative tasks from the company as well as for the transmission of tasks connected with trade, logistics, process controlling and *billing* into the cloud. Increasingly, *cloud computing* services are also provided for end users, for example through the computer operating system Google Chrome, which relies very consistently on cloud resources.

¹¹ The saving potential is enormous; over 40 percent of energy in Germany is consumed in buildings.

¹² See press report by the Verband Deutscher Maschinen- und Anlagenbau (VDMA) dated 06.01.2011 "Gebäudeautomationsbranche rechnet mit weiterem Wachstum in 2011" [Building automation industry anticipating further growth in 2011] at www.vdma.org

For cyber-physical systems, this trend is relevant in the respect that the *business web* allows for the abilities of the embedded systems to be used as services via the internet, thus facilitating a series of web-based business models.

(3) *Social networks and communities (Web 2.0) in two supplementary forms:*

- c) Social networks – the purpose of which is communication and social interaction – bundle large quantities of data and information. This also applies to open knowledge networks: companies increasingly use Wiki systems for the widespread provision of information and knowledge. For companies, users are potential customers and social networks are potential advertising and marketing platforms. With the increasing establishment of profiles and a specialization of participants, the demand for new services is developing, for example for general and domain-specific “*apps*” (*applications*) and networked applications. Devices using Web 2.0, predominantly smartphones and tablets, explicitly and implicitly account for a multitude of sensors; thus, a cyber-physical system based on social networks is suddenly developing. It is necessary to actively use and control this effect.
- d) Communities made up of individual or closely connected groups of developers are driving the innovation. They are usually organized around development platforms; these often deal with *open source* projects, which develop software with open source codes, either in self-organization or under the management of a company or consortium. Other self-organized *communities* are specialised in certain fields of application, i.e. they are driven by specific problems, or are a specialist social network.

An enormous innovation potential for new services and solutions is developing, resulting from the interplay of the

three trends and the evolutionary dynamics of (3) with an increasing demand for solutions from (1) and (2). This potential, in turn, will lead to dynamic changes in markets, in industrial and business sectors and economic ecosystems, as well as to a change in business models.

2.3 CYBER-PHYSICAL SYSTEMS REQUIRE INTERDISCIPLINARITY

Cyber-physical systems are made up of physical systems – i.e. mechanical, hydraulic, electrical and other systems – as well as electronics and software. Sensors, actuators, production engineering, communication and information technology and software engineering are closely linked. The integration of these very different disciplines represents the actual challenge.

For all sectors of system design and control, cyber-physical systems require interdisciplinary, cooperative work in networks and clusters which are dedicated to innovation. This concerns:

- development, production and exploitation;
- operation and maintenance;
- services, consulting, adjustment and extension;
- medium-term and long-term projects relating to strategy development and evolution; and
- comprehensive engineering of systems by corporate clusters sharing strategy and platform cooperation as part of a corporate network, i.e. an economic ecosystem.

Understanding cyber-physical systems and the ability to develop their entire potential further require a coordinated, integrated vision of science, economics and politics.

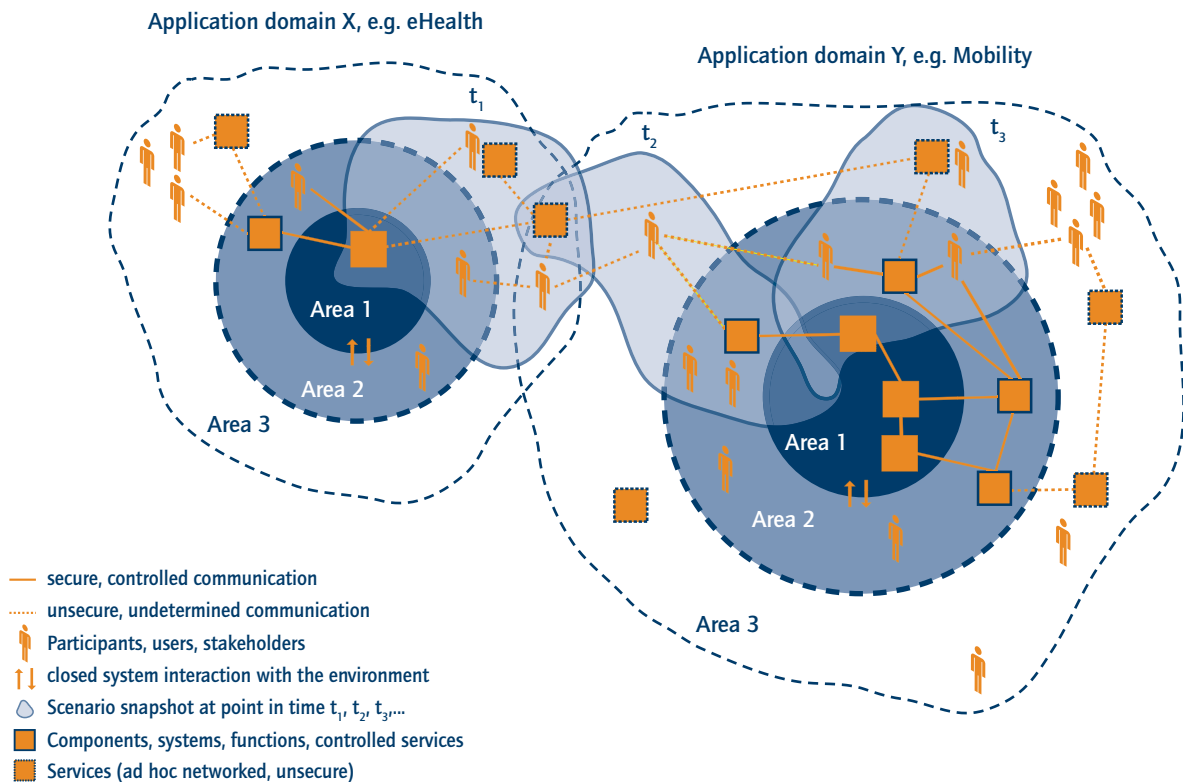
2.4 FROM VISION TO REALITY – HOW DO CYBER-PHYSICAL SYSTEMS COME TO LIFE?

Usually, cyber-physical systems are not designed as completely new systems. Instead, they evolve by networking existing infrastructures with embedded information technology – with the help of the internet, mobile communication services and cloud solutions. The performance and complexity of the newly formed systems become particularly clear in the networking of two or more domains, i.e. when cyber-physical systems from different fields of application, for example mobility and health, are connected and integrated (see Fig. 2).

Fig. 2 shows an onion-like structure of two application domains (mobility and health) and schematically merges their components, user groups and mutual communication relationships. The functional overlaps, which can be characterized as follows, are of particular significance:

- **Controlled core area:** This area comprises conventional, closed, embedded systems of a certain field of application which are characterized by controlled interaction with the environment. One example is electronic toll stations in the Toll Collect system installed on German motorways. If correct handling is ensured,

Figure 2: Schematic illustration of the cross-domain integration of cyber-physical systems



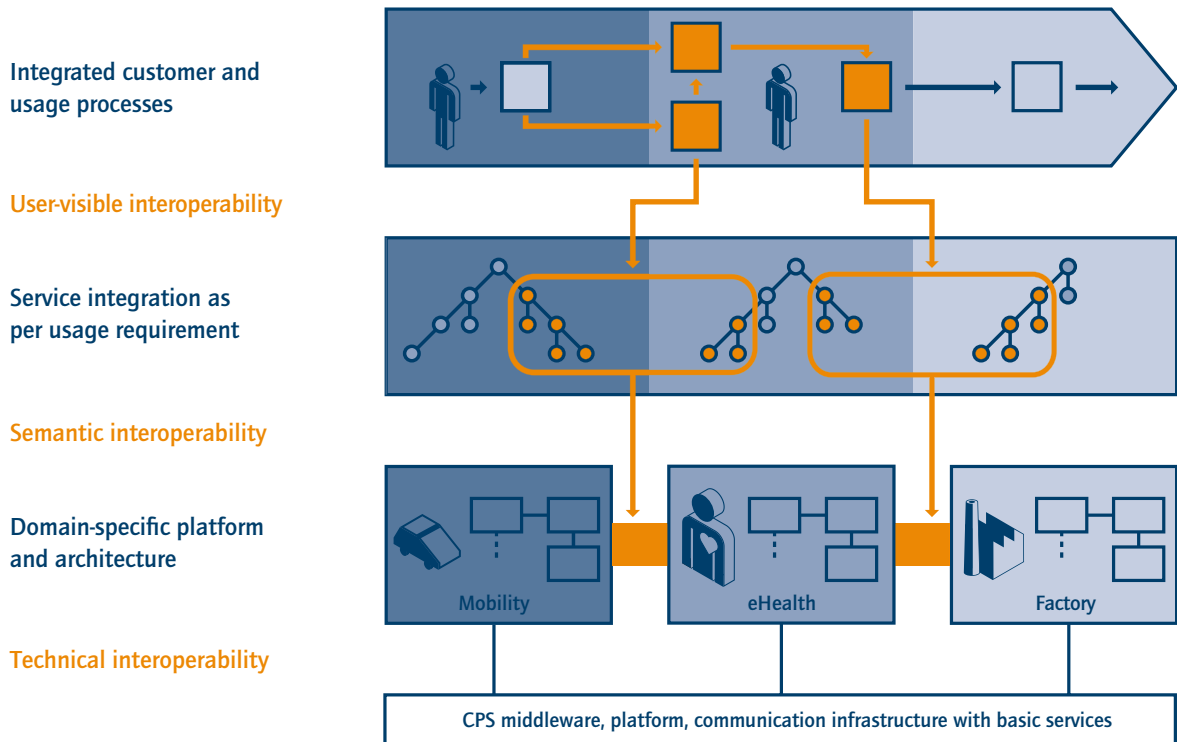
operational reliability and predictability will be guaranteed.

- **Extended field of application:** Here, the systems and components of the field of application cooperate using specified behaviour in predetermined usage situations (example: accounting in logistics). Proper functioning requires users with special training, who comply with the rules, such as general aviation pilots.
- **Cross-domain networking:** Cyber-physical systems in open environments consist of users, actors (also in social networks), services (also those which are provided over the internet) and information with dynamic integration,

uncertain reliability and availability. The challenge of designing these systems is that the users and open systems interact in an ad hoc manner. One example is the dynamic integration of up-to-date information about traffic jams, air and rail delays and date changes into an assistance system, meaning travel can be planned in line with the current situation.

Interoperable and compatible cyber-physical systems, components and services with the relevant interfaces and protocols require a gradual setting-up of standardized, flexible infrastructures and communication platforms (see Fig. 3).

Figure 3: Ideal model of the layers of a cyber-physical system



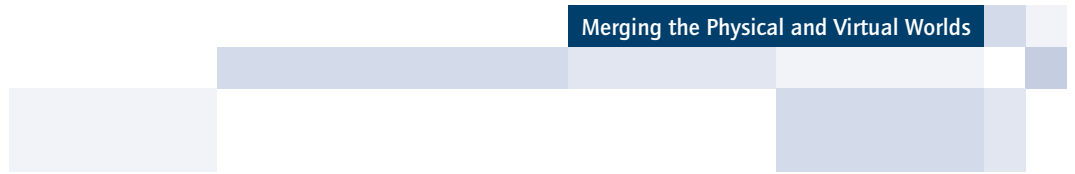


Fig. 3 illustrates the ideal structure of the layers of cyber-physical systems. This includes both the communication infrastructure with basic services (lowest box), as well as the middleware. Based on this, application-specific platforms exchanging their data via interfaces can be set up. Services for targeted access are provided on these platforms. For this, technical interoperability is needed, guaranteeing a consistent interpretation of the data between the services. The top layer shows the application layer accessed by the users.

The decisive factor for networking cyber-physical systems beyond application boundaries is that information from different applications must be semantically compatible. This "semantic interoperability" ultimately enables the interplay of applications.

An overview of the specific abilities of cyber-physical systems is shown in a table in the appendix (Fig. 7); the most important properties are summarized in columns. The following categories are listed in detail:

- embedded systems linked to the physical environment in real time by sensors and actuators;
- "*Systems of Systems*" (SoS) through the networking of embedded systems;
- adaptivity and partial autonomy;
- cooperative systems with distributed control; and
- extensive human-machine cooperation.

The last column summarizes fundamental capabilities and required qualities.

3 FUTURE POTENTIAL OF CYBER-PHYSICAL SYSTEMS – 2025

Cyber-physical systems contribute to finding answers to key challenges of our society and are highly relevant for numerous industries and fields of application. Cyber-physical systems provide companies with support in process optimization and therefore also in cost and time saving, and they provide help in saving energy, thus reducing CO₂ emissions. For private users, the benefits of cyber-physical systems are predominantly in a higher level of comfort, for example in assistance with mobility, in networked safety, in individual medical care and for older people in the field of assisted living.

In the *agendaCPS* study, the following four fields of application - which have particular relevance for Germany - were investigated in detailed scenarios for the period up to 2025:

- **Energy** – cyber-physical systems for the smart grid
- **Mobility** – cyber-physical systems for networked mobility
- **Health** – cyber-physical systems for telemedicine and remote diagnosis
- **Industry** – cyber-physical systems for industry and automated production

The following sections should clarify the scenarios in detail. They are described extensively in the *agendaCPS* project study.

3.1 CYBER-PHYSICAL SYSTEMS FOR THE SMART GRID

Energy supply in Germany and in the rest of Europe is facing an upheaval. Energy that is available at any time from conventional power plants (nuclear power, coal and gas) is gradually being replaced by energy from renewable sources. This change is advocated politically and by society.

Wind and solar energy are not always available to the same degree – depending on the weather and time of day. To date, volatile and decentralised energy has been subject to

greatly differing consumption depending on the seasons and regions. However, for stable energy provision, supply in the electricity network always has to outstrip demand. Decentralised energy and volatile availability require extensive management. To this end, energy conversions (for example storage or energy-gas transformation) can be used, and energy prices can be designed flexibly depending on the availability of power. However, this requires extensive information management which continually records consumer data, creates prognoses about consumption and manages appliances. In order to guarantee reliable energy provision in the future, it is necessary for the electricity grid to become “intelligent”. Energy producers and energy storage facilities, grid management and electricity consumers need to be networked with one another. This will create the “Internet of Energy”, whose implementation has been supported by the German government with the “E-Energy – ICT-based Energy System of the Future” programme since April 2007. The migration paths towards such a “*Future Energy Grid*” are described in an acatech STUDY of the same name to be published at the beginning of 2012. The strong networking via information and communication technology as part of the smart grid will facilitate further functions and services, as well as stable energy supply. Cyber-physical systems form a fundamental technological basis for this.

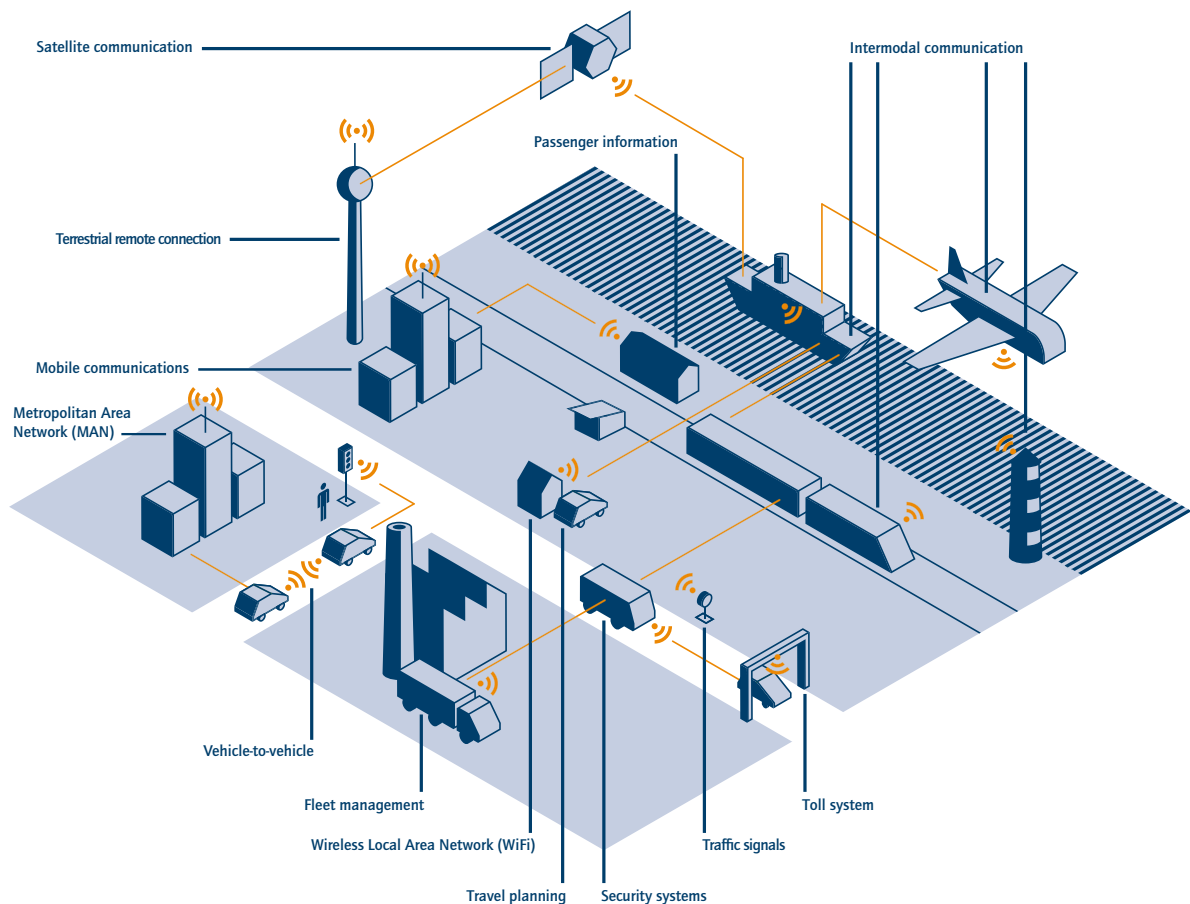
3.2 CYBER-PHYSICAL SYSTEMS FOR NETWORKED MOBILITY

In the field of mobility, i.e. transportation, an extensive networking of the different means of transportation is only possible using cyber-physical systems. This applies to individual vehicles and road users, as well as to the entire transport infrastructure. Networking in cyber-physical systems creates new ways of avoiding accidents, respecting limited energy resources and reducing environmental pollution.

Particularly in the field of electromobility, cyber-physical systems are taking on a key role, as they provide the basis for energy, battery and charge management. However, the potential of cyber-physical systems goes beyond this. For example, they can act as a planning and coordination tool using distributed transport management, and can react to unforeseen situations such as traffic jams. This requires

individual systems to continuously exchange information, for example real-time weather information or information about transport situations, breakdowns and other available alternative means of transportation and routes. Fig. 4 provides a schematic illustration of the different means of transportation and their networking.

Figure 4: Networked mobility through distributed traffic management



The added value of cyber-physical systems for networked transport management is manifold:

- increase in transport safety, for example by recognizing risks and obstacles (including the exchange of information with other road users), optimal transport management and, consequently, avoiding traffic jams;
- higher level of comfort for individual road users, for example through time-saving use of intelligent assistance tools;
- improvement of the ecological balance through lower environmental pollution as a result of improved transport management, resulting in lower CO₂ emissions caused by lower fuel consumption; and
- improved economy due to better exploitation of means of transport and transport infrastructure, as well as accident and damage avoidance, based on the information and services provided.

3.3 CYBER-PHYSICAL SYSTEMS IN TELEMEDICINE AND FOR ASSISTED LIVING

The rapid development of information and communication technology is also advantageous for the health industry. Visions of future medical care in our society are based on extensive networking of patients and doctors as well as health monitoring with the help of modern smart health systems. The acquisition of medical data via suitable sensors for processing and evaluating in real time makes it possible to provide individual medical treatment to patients with long-term illnesses. In the smart health system, individual medical requirements can be taken into account and the increasing number of old people can be better supported and cared for.

With the help of cyber-physical systems, senior citizens are able to continue to live independently at home without

having to give up comprehensive medical treatment. A monitoring service for patients with pacemakers can, for example, warn when vital medical parameters, recorded using sensors, are deviating from normal state. If appropriate, the service can automatically set off an emergency call providing information about the location of the patient. Greater accuracy in medical treatment is facilitated by medical sensor data, information from the patient and from medical staff about the vital data, and the recognition of and reaction to emergency situations. At the same time, it provides a valuable contribution to cost-containment in health care.

The added value of cyber-physical systems for smart health is manifold:

- extensive medical treatment without restricting independence in a person's living situation (for example in ambient assisted living);
- better support and primary care in medical emergencies, for example when travelling;
- CPSs are a basic prerequisite for high-performance solutions in telemedicine and remote medical diagnosis;
- CPS health portals can offer more extensive consultation and support in medical issues than pure information forums.

In times of demographic change, cyber-physical systems are contributing to enabling older people to actively and independently care for themselves for longer, and ensuring that they can participate in society life. This considerably increases their quality of life and provides a significant contribution to the necessary reduction of care costs. Despite all this potential – particularly in the field of smart health – the sensitivity of patient data and the high levels of inertia inherent in the German health system represent a key obstacle to the technological cooperation required for CPS.

3.4 CYBER-PHYSICAL SYSTEMS FOR THE FACTORY OF THE FUTURE

Cyber-physical systems are also of major relevance in industrial production, in order to be able to implement customer requirements. In-house production processes can be optimized, leading to improvements in the ecological balance sheet. Production systems will be set up that are able to react virtually in real time to changes in the market and the supply chain using cyber-physical systems, and which cooperate with ultra-flexibility even beyond company boundaries. This not only makes rapid production in accordance with individual customer specifications possible, the production procedure within companies can also be optimized via a network of globally cooperating, adaptive, evolutionary and self-organizing production units belonging to different operators.

The potential for saving and innovation in such plants is enormous. Without a doubt, plant operators need this development. Germany has many of the necessary competences. However, these are currently too widely distributed - between plant operators and companies in mechanical and systems engineering (manufacturing industry and process industry), logistics, automation technology and the ICT industry.

The initiation of a cross-industry transformation process for cyber-physical systems requires major challenges to

be overcome. This includes coping with new production processes, correct models of production, robust production processes, stable machinery with predictable properties, suitable models and simulation procedures for processes and machinery, safe approaches in artificial intelligence, security and safety within the networks and extreme real-time capacity.¹³

The new effectively "bottom-up" value creation opportunities for production that arise from open networks are also discussed under the keywords "bottom-up economy" and "open production".¹⁴

The added value of cyber-physical systems for smart factories is manifold:

- optimization of production processes by CPS: the units of a smart factory know their fields of activity, configuration possibilities and production conditions and communicate independently and wirelessly with one another;
- optimized manufacturing of an individual customer product through the intelligent compilation of an ideal production system, taking into account product properties, costs, logistics, security, reliability, time and sustainability;
- resource-efficient production;
- tailored adjustments to the human workforce ("the machine follows the human work cycle")

¹³ See Abele/Reinhart 2011 and Vogel-Heuser 2011.

¹⁴ "Vielmehr ist es erforderlich, sich von der Vorstellung eines Produktionsunternehmens als Fabrik im Sinne einer rechtlich selbständigen, zentralisierten Einheit zu lösen, um auch unkonventionelle Entwicklungsmodelle zu ermöglichen." [*In fact, it is necessary to separate oneself from the vision of a production company as a factory in the sense of a legally independent, centralised unit, in order to facilitate unconventional development models as well*] (Wulfsberg/Redlich 2011, p. V.)

4 CHALLENGES FOR GERMANY ARISING FROM CYBER-PHYSICAL SYSTEMS

Far-reaching challenges for Germany are connected with the further development of cyber-physical systems, both of a general and a specific nature. The extensive complexity of the task can be seen in technical, methodological and functional terms in research and development, as well as in usage and the effects of cyber-physical systems on the economy and society. The overcoming or reduction of complexity and the shaping of highly flexible systems are indispensable prerequisites for the long-term success of the development and use of cyber-physical systems.

4.1 SCIENTIFIC CHALLENGES

Heterogeneous, networked structures made of physical systems, electronics and software are created by cyber-physical systems. These systems are giving rise to a new concept of systems and require a comprehensive systemic view. Management of this type of system requires theoretical approaches, which facilitate a merging of classic models of mechanical engineering and electrical engineering with the digital models of computer science. Rather abstract models created by computer scientists for dealing with information and knowledge processing need to be merged with models from the physical world to depict time and space. The requirements of closed, embedded systems – such as reactions in real time, functional safety and absolute reliability – need to be combined with the properties and restrictions of open systems – such as restricted availability and dynamic expandability.

Ultimately, Cyber-physical systems can only be developed efficiently with the help of new models and design methods for networked technical systems (multi-level systems). It is typical for such systems that it is not the optimization of these systems which plays a fundamental role, but the overcoming of their complexity and the inclusion of new functionalities such as the adaptivity of the systems, learning of functions, selforganization and more. To put

it boldly, the different branches of science need to be networked with one another in the same way the technical systems are networked through cyber-physical systems. For example, the networking of antilock braking systems (ABS) and supported steering systems (*Electric Power Steering/EPS*) is impossible without the interdisciplinary linking of methods of mechanical engineering, communication technology and computer science.

The design and development of appropriate systems require approaches that consistently expand the concepts of system engineering in such a way that they can also be used for cyber-physical systems. In this context, there is a need for research within the individual disciplines; it is necessary to prepare discipline-specific approaches for integration into cyber-physical systems. As a key challenge, computer scientists need to find a way for applications with precise real time requirements to work via communication networks whose behaviour is only randomly representable, i.e. under the assumption of probabilities.

The future ubiquitous presence of cyber-physical systems gives science the task of efficiently developing networked technical systems using new models and design methods. In doing so, the technical optimization of the systems will play less of a role. Instead, the handling of complexity and the realization of new functionalities through the adaptivity of the systems and the combination of functions will be at the forefront.

Accordingly, cyber-physical systems require an interdisciplinary networking beyond the boundaries of applications. Relevant IT skills – as an essential part of professional qualifications – become the key to being able to develop cyber-physical systems in Germany and export them from here. This requires new ways of thinking in terms of opening up and creating closer links particularly between both engineering and computer science and other disciplines, for example business management or cognitive sciences. It is

also important to ascribe greater value to interdisciplinary projects in terms of scientific reputation.

At the moment, our education and training systems at schools, colleges and universities, as well as our development processes and methods are only suitable for managing cyber-physical systems to a limited degree.

4.2 TECHNOLOGICAL CHALLENGES

Technologically, cyber-physical systems place new requirements on the controllability of engineering and operation due to their complexity and interdisciplinary character. How should cyber-physical systems be built, controlled and maintained? What is control in open systems like? How can applications with hard real-time requirements be implemented via communication networks that can only be randomly described? A systemic approach to managing the core issues of development, such as the determination of requirements and the architecture design, is needed. This will target issues of interoperability, interfaces, open and proprietary standards, quality, domain models and tools. Managing the determination of requirements is already part of the functional development. Architectural design for cyber-physical systems includes issues of communication topology, reference architectures, open architecture and modular service architecture. In addition, challenges in the fields of **security and safety**, usability and reliability, future proof (capacity to evolve), usage (human-machine interaction, acceptance, ergonomics) are of central importance. In addition, there are issues of **technical implementation** through hardware and mechanics (sensors, actuators, mechanics, energy provision, wired and wireless communication, end devices, *middleware* and platforms). **Managing development and engineering** requires processes and methods such as distributed development, user involvement, integrated methods and models for physical components, electronics and software.

Cyber-physical systems require various applications to be quickly and easily networked with one another, both statically during the development period and dynamically during operation. This requires distinctive **interoperability** on all abstraction levels of the cyber-physical systems. This applies on a technical level, for example with regard to protocols, and electronic and electrotechnical compatibility of the systems, on an architectural level in terms of the interplay of various components, according to a logical design, and especially on a functional level. In interoperability of open systems on functional and semantic levels requires techniques of "*automatic reasoning*", knowledge representation, the *semantic web* and the semantic interpretation of data and services.

Beyond pure interoperability, the **portability of applications** across different levels from the cloud to the end devices with *seamless roaming* via the different wired and wireless networks needs to be defined as an objective (as addressed by the term "compute continuum"). For example, it has to be possible to seamlessly transfer the downloading of a video, which is started on the domestic PC using DSL, to the entertainment system in the car, where the rest of the video is downloaded for child entertainment via a wireless connection.

Virtuality of cyber-physical systems means that the functions of the system in many sectors are independent of materials, locations and devices, as well as detached from physical restrictions, thus creating an image of reality. Of course, virtuality collides with the boundaries of the physical world. Despite this, the geographic autonomy of data, information and services and their independence from specific devices or infrastructure is essential.

Besides the technical command of the virtual level, the consideration and integration of physical processes and physical components connected in cyber-physical systems represent another decisive factor. The interplay of the physical linking of components and their virtual networking is

one of the technical challenges. Above all, the physical components are an important driving force in developing cyber-physical systems, for example in intelligent energy systems.

4.3 ECONOMIC CHALLENGES

Besides their technical development, cyber-physical systems need to be marketed, operated and distributed. However, today's industrial structures in the Federal Republic of Germany are still characterized by largely hierarchically organized and layered supplier networks. It is typical to have a small number of very dominant original equipment manufacturers (OEMs) with major subcontractors in the centre of the network, who then use smaller subcontractors in a number of layers. This generates a large part of the strength of the German industrial structure, i.e. the major companies and the multitude of very successful smaller and medium-sized companies. The particular challenge in Germany will be to promote both the business knowledge as well as a corporate landscape that can generate extensive added value from cyber-physical systems.

Cyber-physical systems support and accelerate the change in our economic system, which began in the mid-1990s as a result of *e-commerce*, away from classic product development and distribution into development and production communities in flexible networks of companies with global services. Fundamentally new business models are being developed as a result of cyber-physical systems, for which infrastructures (platforms, broadband networks) and standards are required.

Previously isolated economic "silos" – i.e. proprietary solutions of companies – are being eliminated by the cross-domain effects of cyber-physical systems and are evolving into open systems. Exchange platforms are developing, through which companies and customers can find one another ad

hoc, reciprocally and dependent on context, and where they then can develop shared markets. As a result, the previous hierarchical relationships between subcontractors, production companies and customers is developing into corporate networks. Competition on the market is shifting from the competition between individual companies to the competition between corporate networks.

The networking components of cyber-physical systems and open standards will support the necessary collaborations and the formation of corporate eco systems. Cyber-physical systems are creating new company roles and functions, such as service aggregators, who collect individual services from suppliers and market them as whole solutions via shared platforms. Up to now, operator models for platforms for cyber-physical systems have been lacking. The knowledge to set these up is largely available.

4.4 POLITICAL CHALLENGES

Politicians are facing fundamental challenges as a result of cyber-physical systems, as the **rules for open systems** still need to be created. The handling of massive volumes of data, which arise as a result of cyber-physical systems, and the management and storage of this information require a high level of **information security**. Public acceptance also depends on data privacy and security, as well as on the question of whether people can trust these systems. There are also issues of safety and liability.

Against this background, it is important to create **legal conditions**, particularly to protect safety-critical infrastructures, and to clarify issues of liability. In particular, the question of the collection and property rights in data relevant for cyber-physical systems, is still unsolved. This includes access rights of third parties and all the regulatory issues connected with this. The flood of primary data created by cyber-physical systems, which is recorded in real time, poses the

question of who is permitted to collect this data and under which conditions, who has access rights to this data or parts thereof and under what prerequisites, and how this data should be managed in terms of organization.

As it is often not practical, economically justifiable or possible to record data on the same subject several times, the question of the openness of databases arises. And last but not least, cyber-physical systems involve **high levels of investment in the technical infrastructure** of systems, hence financing needs to be secured and provided.

Politicians are also faced with the task of **creating the economic conditions** to secure the technical design and to ensure that there are enough qualified specialists.

As a result of cyber-physical systems, technology is becoming involved to a great extent in social and economic processes. For this reason, the political world also needs to initiate a **social discourse** to create an awareness of the various dimensions of cyber-physical systems and to inform the general public about opportunities and risks.

4.5 SOCIAL CHALLENGES

Social willingness to accept this new technology, use it and further develop it is decisive for the success of cyber-physical systems. **Acceptance by users** is a crucial prerequisite for the use of cyber-physical systems. Acceptance means

that users perceive technologically designed systems positively, accept them and are willing to use them. The past has shown that it is extraordinarily difficult to predict acceptance. At the same time, acceptance is very closely dependent on well-designed human-machine interaction. For this reason, issues of acceptance need to be addressed extensively from the very beginning during the design of cyber-physical systems. In this context, privacy, the determination of boundaries for systems and socially desired and legitimated restrictions of the functionality of cyber-physical systems are of central importance.¹⁵

Against this background, it appears to be essential to initiate a **more robust social discourse**, will deal with a series of fundamental issues relating to cyber-physical systems. Examples of such questions include the forms of dependency of people on autonomously deciding systems, legal consequences, values and value systems of people with regard to cyber-physical systems, the question of how interpersonal communication develops under the influence of cyber-physical systems and to what extent it is sensible and responsible to set up large sections of critical infrastructure based on cyber-physical systems. The issue of what measures are needed to limit risk also has to be considered.

¹⁵ See the article "Gesellschaftliche Relevanz Intelligenter Objekte" [Social relevance of intelligent objects] in Herzog/Schildhauer 2009.

5 THESES ON THE DEVELOPMENT OF CYBER-PHYSICAL SYSTEMS IN GERMANY

Time is of the essence for Germany to consolidate its position, especially with regard to the competition with the USA and Asia – Germany's advantage in terms of embedded systems, which currently still exists, could be lost in a few years. The following theses summarize the fundamental statements about cyber-physical systems:

1. **Consolidation of Germany's position relating to cyber-physical systems:** Attractive operator models and public investment in open platforms for cyber-physical systems are prerequisites for their successful realization.
2. **Managing the development of cyber-physical systems:** The development of cyber-physical systems requires the cooperation of all industries and domains in interdisciplinary and collaborative terms during the entire product life cycle (*systems engineering*, standards, interoperability, *open source*).
3. **Cyber-physical systems are part of socio-technical systems:** As cyber-physical systems intervene in work and everyday life in an as yet unprecedented degree in many fields of application, for example in the health sector, public acceptance and acceptance by users is essential for the successful introduction of cyber-physical systems. For this reason, the development of ethically sustainable and legally permitted solutions is a key issue for the scientific and technical communities.
4. **New business models as a result of cyber-physical systems:** As cyber-physical systems work collaboratively and interactively, those companies which specialise in roles conforming to their relevant core competences in corporate networks will be particularly successful, and will develop these roles in such a way that they are aligned to the infrastructure of the overall solution designed for cyber-physical systems.
5. **Key role of SMEs for cyber-physical systems:** The key role of SMEs in terms of providing partial solutions for cyber-physical systems can only develop if collaboration in research and development projects is made easier for these companies.¹⁶
6. **Significance of human-machine interaction:** Technology and applications for cyber-physical systems need to consider user requirements and ensure simple, intuitive operability. The principles for user-friendly and acceptable solutions can be created as early as the technical development process of cyber-physical systems.
7. **"Strengthen Strengths" by research funding:** Germany should "strengthen its strengths" and focus on *embedded systems*, *engineering* and *security* in the field of cyber-physical systems in order to be successful in international competition.
8. **Compensate for weaknesses:** The USA's dominance in terms of the internet and World Wide Web should be mitigated through the consistent development of competence in Germany.
9. **Scientific funding:** The interplay of heterogeneous components in cyber-physical systems - from physical components, electronics and software to components from biology and chemistry - needs to be reflected in science. New forms of interdisciplinary collaboration have to be supported.
10. **Create political answers:** The changes arising from cyber-physical systems require legal and political frameworks for economic action and the safeguarding of social values.

¹⁶ Central result of the acatech online questionnaire on the subject of CPS, in cooperation with the Elektronik Praxis journal.

6 RECOMMENDATIONS FOR ACTION

Specific recommendations for action are derived from these theses.

6.1 CONSOLIDATION OF GERMANY'S POSITION RELATING TO CYBER-PHYSICAL SYSTEMS

The prerequisite for consolidating Germany's position on cyber-physical systems is to rapidly align the country's infrastructure and economic structures with the requirements of cyber-physical systems. To do this, the state should define clear objectives and implement these as part of an overall cyber-physical systems strategy.

acatech recommends:

Mobile internet access and access routes to infrastructure through suitable sensors and actuators have to be supported and developed as technical prerequisites for cyber-physical systems. At the same time, further development of intelligent communication infrastructures needs to be supported in order to handle the future requirements of cyber-physical systems.

acatech recommends:

Development platforms and operator platforms for cyber-physical systems have to be developed and made available, or their setup has to be supported.

6.2 MASTERING THE DEVELOPMENT OF CYBER-PHYSICAL SYSTEMS

The implementation of new dynamic business models places demands on system architecture. The example of integrated services, for example mobility services in con-

nection with operator models for vehicle fleets or patient transportation in healthcare (vehicle equipment, networking), requires comprehensive system architectures and the interoperability of application-specific architectures. The recommendations of the NRMES still apply:

- The development of relevant cross-industry standards (architecture, modelling languages) facilitates new innovations.
- Open standards create new market possibilities.
- A leading role by Germany in the development of cross-discipline solutions for social and economic challenges facilitates early market introduction of such solutions.
- Cyber-physical systems are a field of technology in which all development stages (research, development, production, integration) are accomplished in Germany and where market and technology leadership can be achieved as a result.
- The field of cyber-physical systems as an innovation driver also opens up opportunities for those German industries that have not yet been active in the field of embedded systems.
- Germany can participate to a high degree in the relevant research support programmes of the EU.
- The high privacy protection requirements in Germany and the solutions accompanying this issue lead to advancement in innovation ("IT security made in Germany").

So-called legacy systems are threatening to arise as a result of separate ad hoc developments in the various sub-fields of cyber-physical systems. These legacy systems have a high level of significance in their fields of application, but are very difficult to further develop and integrate with other systems due to their very specific, technical and functional make-up, for example due to a lack of interoperability.

acatech recommends:

Interoperability standards need to be set up which take into account the critical safety and security aspects of the technology and which are also sustainable and capable of promoting export and sales opportunities. Work on standardization by international committees has to be supported.

6.3 CYBER-PHYSICAL SYSTEMS ARE PART OF SOCIO-TECHNICAL SYSTEMS

Only if cyber-physical systems are designed in a way that users find acceptable, will they become successful in the market.

acatech recommends:

The field of human-machine interaction needs to be further developed in terms of research, training and practical implementation in order to achieve sustainable acceptance. The same applies to so-called "*human factors*", from the mental models of the user, and the appeal and usability of cyber-physical systems to the user-specific ability to understand information, solutions and their implications.

Besides usability, safety, security and reliability are further prerequisites for the acceptance of cyber-physical systems.

acatech recommends:

A discourse about the benefits of innovation as a result of cyber-physical systems should be initiated in society. The objective is to involve the general public in the development of cyber-physical systems and to explain security and privacy issues.

acatech recommends:

A working group consisting of academics, lawyers and politicians should be created to develop a comprehensive concept for the handling of personal and internal company data (business secrets) in cyber-physical systems.

6.4 NEW BUSINESS MODELS AS A RESULT OF CYBER-PHYSICAL SYSTEMS

The technical potential of cyber-physical systems facilitates the development of innovative business models which require extensive testing.

acatech recommends:

Specific platforms for cyber-physical systems should be established to explore new business models.

As part of a secondary research project, it would be reasonable and possible to carry out an analysis of such innovative business models based on cyber-physical systems.

acatech recommends:

The economic environment should be taken into account when considering secondary research projects for all key projects relating to cyber-physical systems. The focal points are "business models for new products and product-service systems", "services of cyber-physical systems" and "corporate software for cyber-physical systems".

acatech recommends:

"Showcases" with pilot applications of cyber-physical systems should be used early on to highlight cyber-physical systems, addressing both the relevant professional associations and the public.

6.5 KEY ROLE OF SMES FOR CYBER-PHYSICAL SYSTEMS

Small and medium-sized companies (SMEs), particularly start-up companies in the IT industry, are key participants in the development of the innovation and value-creation potential of cyber-physical systems. They are not only suppliers of individual technical solutions; they are also the ones who connect to platforms in cyber-physical systems with new solutions and services and who can benefit from the newly developing economic eco system. For their formation, cyber-physical systems need SMEs and their strengths, especially in a corporate network concerning cyber-physical systems: traditional and established, as well as small innovative companies are close to their customers, can solve problems more flexibly, concentrate on their core competences and are very effective in this respect.

acatech recommends:

Besides simplified access to research projects, other measures to strengthen SMEs in corporate networks relating to cyber-physical systems are needed. This concerns basic conditions, organizational models and networks. Platforms and joint research projects specifically involving SMEs have to be created.

In addition, the improvement of the conditions for start-up companies will be of major importance for the position of German industry in the field of cyber-physical systems in the future. Obstacles need to be urgently reduced in order to protect the German value chain with all the basic tools needed for the development of the systems, thus preserving the national economy's capacity for innovation. Dependencies with regard to technical availability and speed of innovation need to be removed.

acatech recommends:

Establishment of a start-up "environment" in the field of cyber-physical systems through political, financial, legal and higher educational measures. This includes the promotion of new company start-ups and spin-offs through the provision of more venture capital as well as the establishment of an appropriate eco system. In addition, incentives should be created for established global players regarding technology transfers, start-up investments and pilot projects. Furthermore, secondary research activities are recommended.

6.6 ECONOMIC SIGNIFICANCE OF HUMAN-MACHINE INTERACTION

Human-machine interaction is also of central importance from an economic point of view. In particular, the specific German phenomenon of "*overengineering*" – the creation of a product or service of a higher quality or at greater expense than actually necessary – can be a crucial factor in the development of cyber-physical systems.

acatech recommends:

Human factors in connection with cyber-physical systems need to be comprehensively researched, from classic issues of ergonomics traceability, the integration of adaptive and adaptable cyber-physical systems into work processes and its effects, up to the issue of potential adjustments in social behaviour under the influence of the use of cyber-physical systems.

For cyber-physical systems, consistent customer focus and, thus, user-friendliness and intuitive usability are the key to success.

6.7 RESEARCH FUNDING: "STRENGTHEN STRENGTHS"

Due to the major significance of cyber-physical systems, research funding needs to be aptly focussed on the many challenges. This concerns the ability to develop digital systems in a controllable manner. In this respect, approaches involving the model-based development of product lines and concepts for long-term system evolution are particularly important. This requires fundamental innovation alliances in which cross-domain and interdisciplinary system development is researched in terms of its methods and processes, and then implemented in practice. SPES2020¹⁷, a BMBF-financed research project on the development of a method for the integrated model-based development of embedded systems, can act as a prototype.

Horizontal joint research projects aim to develop methods which can be used as standard in many different fields of application. The focus is on procedures and innovative processes in engineering and techniques to design and implement systems. This includes reference architectures and standards. Two major fields can be defined for research tasks:

- Managing of engineering, processes, methods, support tools and modelling approaches. These technologies must make it possible to build a bridge between system components that are connected to hard physical laws, for example real time, and components that are deliberately abstracted from these physical laws.
- Managing technology for systems. This concerns architectures, platforms – for example middleware –, protocols, algorithms and processes.

Besides such horizontal projects, this also requires vertical projects that do not focus on researching the method and technology, but focus on their use in prominent fields

of application, for example *smart grids*, networked health systems or comprehensively networked automation and production plants. Stimuli need to be provided here to initiate projects in key domains.

acatech recommends:

The funding and campaign programmes within the high-tech strategy and the ICT strategy of the German government should be inspected with regard to cyber-physical systems and be thematically adjusted accordingly. Horizontal and vertical key projects relating to cyber-physical systems have to be linked.

However, care must be taken to ensure that economic principles dominate, activities and concepts are consistently focussed on the market, and that market development is at the forefront.

acatech recommends:

Besides the BMBF smart mobility joint research project ARAMIS (Automotive, Railway and Avionic Multi-Core Systems), that has already been initiated as a result of this study, other vertical projects need to be set up in the following fields of application:

1. **ICT for the smart grid:** This project should concentrate on the issue of ICT architecture for the energy networks of the future and build on the experiences gained in the trial regions of the German initiative E-Energy and in the acatech project on the Future Energy Grid. Here, the modelling of energy networks has to be at the forefront, structuring the requirements for energy networks through the extensive modelling of network structures and the functions and services provided via ICT architectures.

¹⁷ See homepage www.spes2020.informatik.tu-muenchen.de

2. E-health: The health sector is of the utmost importance for cyber-physical systems, as issues concerning embedded systems with regard to sensors and actuators are combined with challenging issues of privacy and safety. This is because the main focus is on the patients, their safety and the protection of their data. There are also further issues in communication and social media. For this reason, we recommend setting up an E-health project that focuses heavily on cyber-physical systems.

3. Cyber-physical systems in production: The use of cyber-physical systems in production systems results in the “smart factory”. Its products, resources and processes are characterized by cyber-physical systems; through its specific properties, it offers advantages with regard to quality, time and costs in comparison with classic production systems. The recommendation is to set up an appropriate project as part of the “Industry 4.0” initiative that was started in 2011 with the objective of removing technological and economic obstacles and promoting the realization and use of smart factories. For the engineering and implementation of cyber-physical systems, the integrative, interdisciplinary development of product and production systems needs to be promoted. This includes the modularization of production systems into production units using model-driven development (*Model Driven Design*).

The following topics relating to *cyber-physical production systems* are of central importance for production engineering:

- further research and development of innovation methods in order to always be able to offer new products for the global market;
- ongoing research into new production processes;
- further scientific penetration of production processes and production machines in order to have correctly established models available that can then be used by the cyber-physical production systems;

- robust, rapid, efficient production processes, which can run safely without ongoing human intervention and checks;
- stable machines with predictable properties and behaviour in order to realize safe automation, even under fluctuating environmental conditions;
- models and simulation procedures for processes and machines in order to present automation systems with methods to assess the consequences of their decisions;
- safe processes for cyber-physical production systems, which can run even under difficult environmental and system conditions and at high speed, in order to ensure that neither humans nor machinery are at risk;
- security in the networks in order to avert misuse, criminal interventions and negligence from the outside;
- extreme real-time capability in order to master even the fastest processes, incidents and interdependencies;
- new operator models;
- hybrid system and architecture models for the specific engineering tasks; and
- sustainable design of production (circular flow economy).

The aforementioned points include lots of keywords providing entry points for technical production research in the field of the smart factory.

Backing up vertical projects with a comprehensive, interdisciplinary research group dealing with cyber-physical systems can guarantee the transfer of generic work results between projects.

acatech recommends:

Innovation alliances should head research projects about the cross-domain development of cyber-physical systems with the focal points of *smart grid, e-health and industry 4.0*.

6.8 COMPENSATE FOR WEAKNESSES

In Germany, competences relating to the internet, including the World Wide Web and *cloud computing*, are significantly less developed compared to embedded systems. Measures are required here since economic competition between cyber-physical systems is carried out with the help of synergies between embedded systems and the control of global networks.

acatech recommends:

A central national research and competence centre for the Internet of Things, Data and Services and the World Wide Web has to be set up, which deals with all issues connected with global networks. These include the technical structure of networks, their architecture and design, the various communication levels and protocols, including the technical facilities for this, technology for the design of data and services and their use, for example using search engines, as well as the issue of *cloud computing* and the associated legal, social and political questions.

6.9 SCIENTIFIC FOUNDATION

The modelling of cyber-physical systems requires the interplay of various disciplines – physics, mechanical engineering, electrical engineering and computer science. However, the principles of cognitive psychology and sociology are also essential; their relevance ranges from models of perception, interaction, knowledge, thought processes and problem solving to system and network models in technological sociology. The focus is on the development of a new discipline concerning the engineering of cyber-physical systems with an integrated perception of the modelling of relevant systems. Models from computer science, electrical engineering and mechanical engineering are merged into an integrated modelling approach on the basis of existing

physical models and drawing heavily on control theory. In detail, this means:

- interdisciplinary modelling of hybrid systems consisting of software, electronics and physical systems, incorporating material science, chemistry and biology;
- concepts for linking those system components that are subject to hard physical laws, for example real time, and those components that are abstracted from these laws via cyber-physical systems;
- consistent development processes based on suitable models for cyber-physical systems; and
- approaches for automation and *virtual engineering* for cyber-physical systems.

In terms of human-centred engineering, integrated hybrid system and architecture concepts are required for:

- distributed analogue/digital control and management;
- human-technology interaction and integrated models of action; and
- socio-technical networks and interaction models.

Cyber-physical systems also require greater technical competence and maturity on the part of the general public when dealing with the ubiquitous CPS technology (as well as with the internet). The requirements extend to virtually all levels of our education system. This concerns primary schools, secondary schools and grammar schools as well as colleges, universities and professional training. The adjustment and redesign of interdisciplinary master's degrees along the lines of cyber-physical systems makes particular sense.

acatech recommends:

German science should continue its programmes on networked systems and focus particularly on cyber-physical systems by according interdisciplinary projects a high level of priority.

acatech recommends:

A working group consisting of scientists and representatives from professional associations as well as the relevant ministries should develop a roadmap with comprehensive recommendations to adapt existing degrees and educational courses (computer science, engineering, business management) to include the requirements of cyber-physical systems.

6.10 CREATE POLITICAL CONDITIONS

The implementation of many of the future scenarios which have been developed in the agendaCPS project requires the storage and management of personal data of the utmost sensitivity – regarding health, financial options, partialities and individual abilities – within the network as well as making such data accessible through secure services. The “Internet and Digital Society” Enquête Commission of the German Bundestag is already working on related issues, and fundamental decisions about the handling of “systems dominating humans” already exist on a European level.

acatech recommends:

The existing legal situation needs to be adapted with regard to the technical security of cyber-physical systems, especially in view of privacy and data protection, data security, and safety and liability issues.

In addition, the effect of cyber-physical systems on resources, particularly energy, needs to be investigated. What costs and risks arise in connection with the progressive permeation of the physical world by information technology? To what degree do cyber-physical systems have an effect on our energy and resource requirements (keyword “metals of noble earths”)?

acatech recommends:

Cyber-physical systems should be taken into account in the energy and resource strategies of the German government. In particular, the transition to renewable energies should be taken into account in an overall strategy for cyber-physical systems.

7 APPENDIX

The overview table shows a summary of the specific capabilities of cyber-physical systems, and the rightmost column summarizes the new skills and key requirements and abilities for practical and sustainably innovative cyber-physical system applications. The challenges in realizing the capabilities of cyber-physical systems, including the clarification and creation of the necessary conditions and social consensus-building, are the core of the research issues and fields of action discussed in the *agendaCPS*.

Aside from research endeavours in the field of the new abilities mentioned and the core technologies of cyber-physical systems, the following integrated activities are required to implement and manage the outlined CPS applications:

- Gradual set-up of reference architectures, domain models and application platforms as a prerequisite for correct situation and context perception, interpretation, process integration and reliable handling/management of the systems. This includes:
 - models of the physical environment, its architecture, participants, tasks, roles and (interaction) relationships, etc.;
 - requirement models (functional and non-functional) of direct or indirect participants (stakeholders, systems, components);
 - application/reference architectures: process models, function/service architectures and interaction templates, as well as realization architectures (logical architectures, for example, to realize specific security or performance requirements; hardware and software architectures, or even specific platform and communication architectures), organizational conditions and standards, etc.;
 - quality models as well as models for domain or business rules, target models or company-specific models to inspect and validate CPS services and applications.

- Specific norms and standards for the qualified development and certification of systems.

There is a series of challenges for this setup, which are also of significance for the research and development of corresponding technologies and concepts. Besides the differences in the dynamics and culture of the involved application fields, systems, participants and disciplines, the challenges are:

- the increasing loss of control in open (social) environments with networked and sometimes autonomously interacting systems and participants, and the questions, methods and safeguarding concepts connected with this;
- the reliability of the systems with regard to safety, IT security and privacy as well as other non-functional requirements, for example performance and energy efficiency;
- the protection of (business-) knowledge in open value networks (CPS eco systems);
- the uncertain and distributed risks accompanying cyber-physical systems as well as their assessment and evaluation by individual systems and participants. Risk assessment is virtually impossible in terms of quantity and only subjectively possible in terms of quality;
- cyber-physical systems acting as representatives (agents) of social and economy participants (humans, groups) and being required to conduct appropriate and fair negotiation and the resolution of any arising conflicts of objectives;
- regulations for the (partially) autonomous actions and decision-making on the part of the systems;
- the
 - required conditions¹⁸ and
 - the domain/quality models, rules and policies (compliance regulations) to be negotiated in a legally binding manner

¹⁸ For example, the necessary CPS infrastructure, its safety and quality, standardisation, standards to be complied with and legal conditions etc.

Overview table of the capabilities of cyber-physical systems

(1) CYBER-PHYSICAL, SENSORS/ ACTUATORS, NETWORKED (LOCAL-GLOBAL), VIRTUAL, REAL-TIME MANAGEMENT	(2) SYSTEMS OF SYSTEMS (SOS), CONTROLLED NETWORK WITH DYNAMIC BOUNDARIES	(3) CONTEXT-ADAPTIVE AND (PARTIALLY) AUTONOMOUS SYSTEMS
<ul style="list-style-type: none"> - Parallel data collection (sensors), fusion, processing of physical data from the environment, local, global and in real time (Physical Awareness) - Interpretation regarding achievement of objectives and tasks of the CPS - Acquisition, interpretation, deduction, prediction of faults, obstacles, risks - Interaction, integration, rules for and control of CPS-components and functions - Globally distributed, networked real-time control and regulation 	<ul style="list-style-type: none"> - Interpretation of context and situation data over several levels, depending on different application situations - Systematic selection, incorporation, coordination and use of services – depending on situation, local and global objective, and behaviour - Service composition and integration, decentralised control: recognition of missing services, data, functions and active search and dynamic integration - Self-organization - Evaluation of benefit and quality required for the application (QoS, overall quality) of components and services being incorporated – also regarding possible risks - Reliability and compliance with respect to guaranteed QoS - Controlled access to system's own data and services 	<ul style="list-style-type: none"> - Comprehensive, continuous context awareness - Continual collection, observation, selection, processing, evaluation, decision-making, communication of context data, situation data and application data (often in real time) - Systematic adaptation of the interaction, coordination, control with/of other systems and services. - Recognition, analysis and interpretation of plans and intentions of objects, systems and participating users - Model creation for application field and domain, participants, including their roles, objectives and requirements, available services and tasks - Assessment of objectives and steps, taking into consideration alternatives with regard to costs and risks - Self-awareness in terms of knowledge about own situation, status and options for action - Learning of, for example, modified work processes, logistics processes, habits, interaction, etc. and corresponding behaviour adaption - Capacity for self-organization
→ → Increasing openness, complexity, autonomy, "smartness" and		

(4) COOPERATIVE SYSTEMS WITH DISTRIBUTED, CHANGING CONTROL	(5) EXTENSIVE HUMAN/SYSTEM COOPERATION	KEY CAPABILITIES AND NON-FUNCTIONAL REQUIREMENTS QUALITY IN USE, QUALITY OF SERVICE (QOS)
<ul style="list-style-type: none"> - Distributed, cooperative and interactive perception and evaluation of the situation - Distributed, cooperative and interactive determination of the steps to be carried out – depending on the evaluation of the situation, on the objectives of individual participants and on the objectives of the community these participants belong to (local vs. global objectives) - Subsequent coordinated assessment and negotiation of the decision ultimately taken, i.e. self and shared control and decision-making autonomy - Decision-making on the basis of uncertain knowledge - Cooperative learning and adaption to situations and requirements - Estimation of the quality of own and external services and abilities - Coordinated processing of mass data 	<ul style="list-style-type: none"> - Intuitive, multimodal, active and passive HMI – support (simplified control) - Support of a broader (space, time) and enlarged perception and capacity to act for individuals and groups - Recognition and interpretation of human behaviour including emotions, needs and intentions - Acquisition and evaluation of data concerning state and context of human and system (extension of perception and evaluation skills) - Integrated and interactive decisions and actions between systems and individuals or groups - Ability to learn 	<ul style="list-style-type: none"> - "X" awareness (correct perception and interpretation) of <ul style="list-style-type: none"> - Situation and context - Self-awareness, third party-awareness, human awareness (status, objectives, intentions, ability to act) - Learning and adaption (behaviour) - Self-organization - Cooperation, negotiation and decision-making (within defined boundaries – compliance) - Decision-making on the basis of uncertain knowledge - Provision and maintenance of QoS guarantees - Comprehensive policies for safety and security - Transparent HMI, shared control, integrated situation evaluation and predictable actions - Risk management - Proactive, strategic and reliable actions - Privacy protection

evolution of the systems (with disruptive effects in the fields of application) → →

- which have to be defined in an interdisciplinary manner (socially comprehensive) along with the aforementioned challenges;
- the open question of how to achieve the most predictable and reliable human-computer interaction (HMI), which is required by humans for integrated actions, meaning for example
 1. simple and intuitive HMI despite multi-functional services and usage options;
 2. semantic integration, depending on situation, process and action context (local, regional, global);
 3. passive HMI, i.e. the conscious and unconscious observation and monitoring of humans or groups with the challenges of interpreting the observed behaviour correctly or in the desired manner;
 4. problems of continual attention (vigilance) and the inherent loss of control for humans through the use of cyber-physical systems; and
- resulting from (1) to (4), the cautious evaluation of complex situations including prioritization, integration and use of features¹⁹.

¹⁹ Functions, services

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